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QUARTERLY PROGRESS REPORT NO. 5

Contract No. AF 19(122)-7, Items II & III

December 1, 1952 to February 28, 1953

Item II: Reliability Research
Item III: Coding Circuitry

Prepared by

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V-1959

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RELIABILITY RESEARCH AND CODING CIRCUITRY

ABSTRACT

This report summarizes work performed under the "Reliability Research" and "Coding Circuitry" items of the contract during the period from November 15, 1952 to February 15, 1953. These items are primarily concerned with improving the overall reliability of a future IFF system.

Theoretical consideration is given to various methods for improving system reliability; namely, the use of multichannel transmission, redundancy coding to combat noise, and optimum-filtering techniques. Progress is reported on the construction of a pulse-train correlator designed to improve the reliability of IFF detection in the presence of pulse jamming. This includes related work on equipment to be used in the operational testing of the correlator once it is completed. Also covered is progress made in the development of a reliable transistorized shift register, and on a transistor-testing program.

Personnel and Administration

1. Martin W. Essigmann, Coordinator (two-fifths time Item II, one-fifth time Item III, engineer)
2. Sze-Hou Chang (half-time engineer Item II from December 13, 1952)
3. George E. Pihl (one-fifth time Item II, one-tenth time Item III, engineer)
4. John S. Rochefort, liaison man (four-fifths time Item II, one-fifth time Item III, engineer)
5. Harold L. Stubbs (half-time mathematician Item II)
6. Thomas P. Cheatham, Jr. (one-fourth time engineer Item II from December 15, 1952)
7. Walter H. Lob (full-time physicist Item II)
8. Louis J. Nardone (full-time engineer Item III)
9. Myron L. Bovarnick (full-time engineer Item II)
10. Jacob Wiren (four-fifths time engineer Item III to January 23, 1953; full-time from January 24, 1953)
11. George W. Ogar (full-time engineer Item II, December 15, 1952 through December 19, 1952)
12. Walter Goddard (two-fifths time Item II, one-fifth time Item III, technician)
13. Mary D. Reynolds (two-fifths time Item II, one-fifth time Item III, secretary)
14. Lawrence J. O'Connor (full-time cooperative student assistant Item II through January 23, 1953; part-time assistant Item III from January 26, 1953)
15. John J. Kelly (full-time cooperative student assistant Item II through January 23, 1953)
16. Charles U. Knowles (part-time assistant Item III through January 24, 1953; full-time cooperative student assistant Item II from January 26, 1953)
17. Robert H. Lawson (full-time cooperative student assistant Item II from January 26, 1953)

The engineering staff assigned to these items of work under the contract was increased during this report period by the addition on a part-time basis of Dr. Sze-Hou Chang, and Dr. Thomas P. Cheatham, Jr. Dr. Chang has been continuously employed on work under this contract since its establishment at Northeastern, his other work being under Item I. Dr. Cheatham is presently a Research Fellow at Harvard University, where his current work is concerned mainly with the statistical approach to communications. Previous to his association with Harvard, he served at M.I.T. and Boston University.

Work was begun during this report period under funds provided by Modification No. 10 to the contract. This modification authorized the beginning of work on coding circuitry and transistors as applied to IFF. This work is covered by Item III of the contract.

b. Communications

1. Correspondence

Listings of all non-expendable property received for use under this contract have been sent to the Research Accountable Property Officer under the dates of November 30, 1952, December 31, 1952, and January 31, 1953.

2. Conferences

December 15, 1952. Conference at AFCRC among E. Samson, C. Hobbs, B. Mills, C. Ryan, W. Bishop, R. Wagner, and R. Bradbury all of AFCRC, and S. Chang, M. Essigmann, J. Rochefort, L. Nardone, W. Lob, G. Pihl, and J. Wiren of Northeastern.

The purpose of this conference was to obtain information upon which work under Item III (Coding Circuitry) was initiated. It was agreed that this work would begin with the design, construction, and evaluation of a reliable shift register. It was also agreed that the transistor-test program would be continued as a supporting part of the work under this item. R. Wagner and R. Bradbury were named as Project Engineers for the coding circuitry and transistor testing programs, respectively.

January 6, 1953. Visit made by S. H. Chang, M. W. Essigmann, and J. S. Rochefort to Dr. R. C. Hergenrother and A. S. Luftman of the Raytheon Manufacturing Company.

The purpose of this visit was to observe a demonstration of a storage tube being developed at Raytheon that may have application in the studies on correlation methods currently carried on at Northeastern.

J. S. Rochefort, as liaison man between AFCRC and Northeastern, has kept in constant contact with AFCRC to fulfill this obligation. In addition, L. Nardone, J. Wiren, and C. Knowles have made many visits to AFCRC in order to obtain information upon which to base work under Item III.

3. Meetings Attended

December 27-30, 1952. Annual Meeting of the Institute of Mathematical Statistics at Chicago, Illinois.

H. L. Stubbs attended the sessions of this meeting to better inform the Northeastern group of new developments in the field of statistics that may be applicable to the communications problems being studied under Item II.

c. Statement of the Problem

Item II of the contract is concerned with the study of the communication aspects of the IFF problem with the aim to determine methods for improving the performance reliability of IFF systems. The specific system assumed for the present studies is one in which an n-digit binary number is transmitted as a challenge over a single channel to a transpondor where the challenge is encoded into an r-digit reply. The reply is transmitted to the responsor, also over a single channel, where it is compared with a locally encoded version to determine whether or not it is correct.

The present studies are concerned with methods for improving the transmission reliability of the ground-to-air and air-to-ground links of the proposed system. These two links differ in that the correct reply is available at the terminal of the air-to-ground link, thus providing the possibility of applying prevalent cross-correlation techniques in the reception of the coded reply. Less powerful means must be resorted to at the airplane since no a priori knowledge as to the challenge can be assumed. Atmospherics, enemy noise and pulse jamming, and enemy attempts at interrogation are being considered as factors which need to be combatted in devising systems to provide improved transmission reliability.

The aspect of cryptographic security introduced by the presence of two encoders in the general system is not a part of the present problem. The system is assumed to be secure against an enemy who can only listen.

Item III is concerned with practical aspects of the coding circuitry involved in the system. Specifically the beginning work involves the design, construction, testing, and evaluation of a reliable shift register employing transistors for use in the two encoders of the system described above. The present state of transistor development is such that a transistor testing program is required in order that the necessary data be available for circuit-design purposes.

d. Methods of Attack

The problem of reliability has been divided into two parts: system reliability and equipment reliability. The former refers to the performance of the system if all equipment operates perfectly, while the latter refers to the performance of the equipment alone. System reliability has received major emphasis in the past because it has been felt that techniques for obtaining the maximum system reliability should receive primary investigation. Once the system offering maximum reliability has been selected, then major emphasis should be placed on design and procurement of equipment which will allow maximum equipment reliability to be realized. Consequently, during this report period, under Item II consideration has been given to factors influencing system reliability and to design and construction of equipment for evaluating certain techniques for improving the reliability of systems. Under Item III is included the work that can be appropriately classified as part of the general problem of equipment reliability.

System Reliability

General Considerations

In approaching the problem of system reliability, the first step was to enumerate the factors which might reduce reliability. They include "atmospherics" and receiver noise, inadequate space resolution, garbling and fruit, as well as jamming and deception on the part of the enemy. Since it appears that interference by the enemy constitutes the major threat to reliable operation, it has been given the most attention in the work done thus far.

The effects of enemy interference by means of jamming can be minimized by either minimizing the possibility that signal and jam will arrive simultaneously at the receiver, or by incorporating equipment in the receiver for improving signal detection in the presence of jamming. The possibility of simultaneous reception of signal and jam can be reduced by directional communication equipment, while signal detection in the presence of jamming can be improved by redundancy coding, filtering, and correlation detection.

Directional communication could be achieved if airplanes as well as ground stations were equipped with narrow-beam antennas. For certain applications (AIC for example) it has been suggested that airplanes could be required to approach interrogators along certain prescribed courses. A narrow-beam antenna mounted in the nose of an airplane would be sufficient and enemy jamming could only be effective if the jammer were within the beam angle of either ground station or airplane.

A general-purpose directional communication system would require a narrow-beam rotating antenna on the airplane. This system has been discussed in detail in a previous report.* However, the development of a light-weight rotating antenna for airborne use would require several years and is not within the scope of this contract. Consequently this type of directional communication system is no longer under active consideration.

A survey was initiated in the past to obtain factual data so that a comparison could be made between S and X-band frequencies. The survey was primarily motivated by the necessity of light-weight equipment for the rotating-antenna system mentioned above. However, factual data from a study of this type would be useful in determining the optimum operating frequency for any IFF system. The survey included: (1) obtaining world-wide climatological data, (2) obtaining data giving centimeter-wave attenuation as a function of rainfall, and (3) determining the relation between equipment size and system power requirements at various wavelengths. In view of the magnitude and specialized nature of a study of this type, the remainder of the survey will be carried out by the Propagation Laboratory of AFCRC.

Consideration of any communication system (whether or not enemy jamming is considered) gives rise to the question as to what type of signal is most desirable. From the standpoint of most efficient utilization of bandwidth it appears that the optimum signal is one with a Gaussian amplitude distribution and a flat frequency spectrum. Consequently consideration is currently being given to the use of noise-like signals for communication purposes. In this report period a comparison has been made between single and multi-channel transmission of such a signal in the presence of noise. From the practical standpoint, however, the use of a pulse train as a signal is more desirable at the present time in view of the state of the art in the development of communication equipment. Consequently pulse trains will continue to be used for challenges and replies in the system under consideration until a more exhaustive study of the use of noise-like signals indicates that a change is definitely warranted.

The specific system under study is one in which an n-digit binary number is transmitted as a challenge to the airborne transpondor where it is encoded into an r-digit reply. Since any particular challenge or reply may contain

* Quarterly Progress Report No. 2 dated May 31, 1952.

anywhere from 1 to n, or 1 to r, pulses respectively, the power transmitted is not constant from one challenge, or reply, to the next. This is a disadvantage from the standpoint of duty cycle, error detection, and threshold setting for correlation detection. It would be better for these purposes if a fixed number of pulses were used in challenges and replies. This could be accomplished by the use of an n-pulse challenge and an r-pulse reply if each pulse had two possible positions - one position to represent a one and the other to represent a zero. Consequently it is suggested that the system under study be one that meets these standards.

Since pulse trains are used for challenges and replies it has been convenient to divide jamming into two types: pulse jamming and noise jamming. Of the two, pulse jamming appears to be the more pernicious because of its resemblance to the signal. If a jamming pulse happens to coincide with a zero-digit position of the signal then the "correct" pulse train cannot be separated from the jamming pulse without _a priori_ knowledge of the correct signal. The effects of noise jamming on the other hand can often be reduced by filtering as discussed below.

If a directional communication system is not employed then signal detection in the presence of jamming can be improved by redundancy coding, correlation detection, and filtering. Several methods which fall under the heading of redundancy coding have been considered for combatting noise jamming. They include transmission of a number and its complement, the use of additional digits for error detection and correction, restriction to a specific number of pulses in a pulse train, and coding to match the channel capacity as defined by Shannon.

Cross-correlation of pulse trains has been shown to provide an effective means of overcoming the effects of pulse jamming. This method can very well be used at the ground station of a ground-to-air IFF system, since the correct reply is available there. A pulse-train correlator has been developed for this purpose and is presently under construction. Cross-correlation could also be used at the airplane if challenges were transmitted in a pre-arranged sequence which could be duplicated at the airplane. This would require storage at the airplane, and since storage appears to be undesirable other means are being sought for improving the reliability of the ground-to-air link.

Optimum filters which sacrifice signal shape and merely indicate when the signal occurs have been shown to be the equivalent of cross-correlation. In the presence of noise jamming, the impulse response of such a filter should be the backwards version of the signal waveform. Since storage at the airplane is undesirable a different filter cannot be available to match each possible pulse train. However it has been shown that some improvement in signal-to-noise ratio can be obtained if only one filter is used to evaluate each pulse in the pulse train individually. Such a filter would be matched to a single pulse and would be an asset at both the airplane and the ground station. In order to verify and demonstrate the theory a matched filter has been constructed for 0.6-μs video pulses. Data relative to signal-to-noise ratio improvement will be obtained during the next report period.

When applying the above result in the design of a receiver, it appears that the proper place to make use of the matched-filter technique is the i-f amplifier. Since the second detector is inherently a non-linear device, there is considerable doubt that small signals can be recovered reliably from noise by any post-detection means if the signal-to-noise ratio is less than one at the input to the second detector. Consequently it appears best to maximize the signal-to-noise ratio before detection. A matched filter for the i-f section is being developed and the test program will include predetection filtering.

The block diagram of the proposed test set-up is shown in Fig. 1*. The test equipment can be used to simulate either the ground-to-air or air-to-ground link of an IFF system working in the presence of pulse jamming, noise-modulated carrier jamming, and broad-band noise jamming. Figure 1 illustrates the use of the test equipment to simulate the air-to-ground link of the system under study.

Multi-channel Transmission

The question often arises as to what is the relative merit of sending a signal through a single channel or through n channels. This question, in general, cannot be answered in simple terms, because the transmission efficiency of any system depends, among other things, upon the properties of the signal and noise, and the threshold effect of the system. If the amplitudes of both signal and noise are of Gaussian distribution and if the threshold effect is discounted, then there is always an increase in the average information when the signal power is divided equally into n channels and when the noise power in each channel remains the same.

Let x = signal to be received

y = interfering noise

with $$p(x) = \frac{1}{\sqrt{2\pi a^2}} e^{-\frac{x^2}{2a^2}} ; \qquad a^2 = \text{mean power of signal}$$

$$p(y) = \frac{1}{\sqrt{2\pi b^2}} e^{-\frac{y^2}{2b^2}} ; \qquad b^2 = \text{mean power of noise}$$

Let $$z = x + y$$

then $$p(z) = \frac{1}{\sqrt{2\pi(a^2+b^2)}} e^{-\frac{z^2}{2(a^2+b^2)}}$$

and $$p_x(z) = p(y = z - x) = \frac{1}{\sqrt{2\pi b^2}} e^{-\frac{(z-x)^2}{2b^2}}$$

* The figures are included in the Appendix.

The entropy of the source is given by

$$H_0(x) = -\int_{-\infty}^{\infty} p(x)\log p(x)dx$$

$$= \int_{-\infty}^{\infty} p(x)\log\sqrt{2\pi a^2}\,dx + \int_{-\infty}^{\infty} p(x)\frac{x^2}{2a^2}\,dx$$

$$= \log\sqrt{2\pi a^2} + \frac{a^2}{2a^2}$$

$$= \tfrac{1}{2}\log 2\pi a^2 e$$

The information obtained about the source from a measurement of $z = x + y$ is given by $H_0(x) - H_z(x)$ where the conditional entropy

$$H_z(x) = -\int_{-\infty}^{\infty} p(z)dz\int_{-\infty}^{\infty} p_z(x)\log p_z(x)\,dx.$$

Using Bayes' theorem,

$$p_z(x) = \frac{p(x)\,p_x(z)}{p(z)}$$

$$= \frac{1}{\sqrt{2\pi a^2}}e^{-\frac{x^2}{2a^2}}\frac{1}{\sqrt{2\pi b^2}}e^{-\frac{(z-x)^2}{2b^2}}\sqrt{2\pi(a^2+b^2)}\;e^{\frac{z^2}{2(a^2+b^2)}}$$

$$= \frac{1}{\sqrt{2\pi\frac{a^2b^2}{a^2+b^2}}}\,e^{-\frac{a^2+b^2}{2a^2b^2}\left(x-\frac{a^2}{a^2+b^2}z\right)^2}$$

and hence,

$$H_z(x) = \int_{-\infty}^{\infty} p(z)dz\left[\tfrac{1}{2}\log\frac{2\pi a^2b^2}{a^2+b^2}e\right]$$

$$= \tfrac{1}{2}\log\frac{2\pi a^2b^2}{a^2+b^2}e$$

We therefore find that the average amount of information received about the signal from a measurement z is given by

$$H_{R1} = H_0(x) - H_z(x) = \tfrac{1}{2}\log\left(1+\frac{a^2}{b^2}\right)$$

If we divide the signal power into n channels such that the probability density of each channel becomes:

$$p^{(1)}(x) = \frac{1}{\sqrt{2\pi\frac{a^2}{n}}} e^{-\frac{x^2}{2\frac{a^2}{n}}}$$

then the total transmitted information is

$$H_{Rn} = \frac{n}{2} \log \left(1 + \frac{a^2}{nb^2}\right)$$

It is observed that the average information as to what signal was transmitted has been increased.

Let $r_1^2 = \frac{a^2}{b^2}$ and use the logarithm to the base 2, then

$$H_{R1} = \tfrac{1}{2} \log_2 (1 + r_1^2) \text{ bits}$$

$$H_{Rn} = \frac{n}{2} \log_2 \left(1 + \frac{r_1^2}{n}\right) \text{ bits}$$

and

$$\lim_{n\to\infty} H_{Rn} = \tfrac{1}{2} r_1^2 \quad \text{bits}$$

These are plotted as Fig. 2 in the Appendix.

An alternative view of the above analysis can be obtained by the use of the formula of the channel capacity.[1] For a single channel with bandwidth W_1 and an average signal-to-noise power ratio r_1^2, the capacity is

$$C_1 = W_1 \log_2(1 + r_1^2) \text{ bits/sec.}$$

When the signal power is divided equally into n channels, the total capacity is

$$C_n = n W_1 \log_2\left(1 + \frac{r_1^2}{n}\right) \text{bits/sec.}$$

The connection between the H_R's and the C's is due to the fact that the channel capacity is defined as the maximum rate of transmission. When both signal and noise belong to random Gaussian processes having flat spectra up to W_1, the maximum rate of transmission is $2W_1H_{R1}$ which is equal to C_1.

The advantage of multiple-channel over single-channel transmission depends upon how efficiently the ideal channel capacities are utilized. In the case of pulse-code modulation, to insure an error less than 10^{-6}, a threshold value of $r_1^2 = 100$ (20 db) is needed.[2] (This does not assume the use of matching filters). Any multiplexing which tends to make the ratio below this threshold results in rapid loss of information.

Redundancy Coding

One of the methods which has been considered for obtaining reliable transmission of pulse trains in the presence of noise is that of increasing the length of each pulse train and utilizing the resulting redundancy. The simplest procedures of this type are repetition of the complete pulse train and transmission of the complement following the number. Somewhat more complicated are the codes devised by R. W. Hamming[3] which prescribe procedures for detecting or correcting errors up to an assumed maximum number. Still more complex, but capable of achieving an arbitrarily small chance of error when the probability distribution of the noise is known, are codes based on information theory.[1,4] Some further considerations on this latter method are given here to supplement the discussion in earlier reports.

It should be pointed out that the simple model assumed in this analysis* is strictly applicable only for video transmission, since the assumption that signal and noise are additive is not valid for the envelope of a carrier after detection. For this latter case, the conditional probabilities, when a pulse is transmitted, for correct or incorrect decision by a threshold device, should be written

$$p_{11} = \int_T^\infty p(y)dy$$

$$p_{12} = \int_0^T p(y)dy$$

where y is the envelope of signal and noise combined, and T is the threshold level. Thus any further conclusions as to the optimum value of T depend on the relation between p(y) and p(N) where N is the envelope of noise alone. Also it may be pointed out that the model of a monotonically decreasing p(N) used in the earlier report would be applicable to the output of a square-law detector, for which

$$p(N) = \frac{1}{2\sigma^2} e^{-\frac{N}{2\sigma^2}}$$

rather than to that of a linear detector for which

$$p(N) = \frac{N}{\sigma^2} e^{-\frac{N^2}{2\sigma^2}}$$

where σ is the r.m.s. value of the noise before detection.** For this latter Rayleigh distribution, the choice of T which maximizes $p_{11} + p_{22}$ (i.e., the sum of the conditional probabilities of correct decisions when a pulse is present or not present) can easily be calculated if the additive assumption is used. The following values were calculated for three choices of σ in terms of S, the signal amplitude. P_1 and P_2 are the probabilities of

* See Quarterly Progress Report No. 2, dated May 31, 1952, pp. 8-11.
** See page 61 of reference 5.

transmitting a pulse or no pulse in the ideal code which matches the channel capacity C, and Q_1 and Q_2 are the probabilities that pulse or no pulse will be received. C is given in bits per symbol.

σ	T	p_{11}	p_{12}	p_{21}	p_{22}	C	P_1	P_2	Q_1	Q_2
.5S	1.10S	.98	.02	.09	.91	.71	.52	.48	.56	.44
S	1.54S	.86	.14	.30	.70	.25	.52	.48	.59	.41
2S	2.50S	.76	.24	.46	.54	.07	.54	.46	.62	.38

In calculating C, P_1, etc., from a given matrix $[p_{ij}]$ of conditional probabilities, certain simplifications can be made in the equations used previously and given on page 46 of reference 1, namely,

$$P_k = \sum_{t=1}^{n} h_{kt} \exp\left[-C \sum_{s=1}^{n} h_{st} + \sum_{s=1}^{n} h_{st} \sum_{j=1}^{n} p_{sj} \log p_{sj}\right] \qquad k = 1,2,\ldots, n$$

$$\Sigma P_k = 1$$

In the first place, $\sum_{s=1}^{n} h_{st} = 1$ for all t, as a consequence of the facts that $\sum_{j=1}^{n} p_{ij} = 1$ for all i, and that $[h_{st}]$ is defined as the transpose of the inverse (assumed to exist) of $[p_{ij}]$.

$$\text{Since} \quad \sum_{j=1}^{n} p_{ij} h_{sj} = 1 \quad \text{if} \quad s = i$$

$$= 0 \quad \text{otherwise,}$$

we obtain by addition $\sum_{j=1}^{n} p_{ij} a_j = 1$ where $a_j = \sum_{s=1}^{n} h_{sj}$. But for $i = 1, 2, \ldots, n$ these form a set of n independent linear equations in the n quantities $a_1, \ldots, a_n$, and hence there is exactly one simultaneous solution since we have assumed that the determinant $|p_{ij}| \neq 0$. But $a_1 = a_2 = \ldots = a_n = 1$ is obviously a solution of each equation, and therefore it is the only solution.

Also, as shown on page 3-18 of reference 6, a simpler set of equations can be obtained for the Q_t than for the P_k, using the relation $Q_t = \sum_{k=1}^{n} P_k p_{kt}$. This is equivalent to $P_k = \sum_{t=1}^{n} Q_t h_{kt}$ and comparison with the previous equations for P_k gives $Q_t = \exp\left[-C + \sum_{s=1}^{n} h_{st} \sum_{j=1}^{n} p_{sj} \log p_{sj}\right]$ $t = 1,2,\ldots, n$

$$\sum_{t=1}^{n} Q_t = 1$$

This leads to a simple explicit solution for C:

$$C = \log \sum_{t=1}^{n} \exp\left[\sum_{s=1}^{n} h_{st} \sum_{j=1}^{n} p_{sj} \log p_{sj}\right]$$

Filtering

Since it is not desirable to store challenges at the airplane, cross-correlation of the entire pulse-train cannot be accomplished at the transpondor. However, since the challenge is known to consist of pulses, cross-correlation can be accomplished on a digit-by-digit basis. As such the correlator cannot be used to determine if the "correct" pulse train has been received, but rather its output can be used to determine which digit positions contained pulses.

It has been shown that digit-by-digit cross-correlation can be accomplished by matched filtering. The optimum filter for this purpose is that filter which has an impulse response which looks like the backwards version of the pulse used to represent a <u>one</u> in the pulse train. If the pulse is represented by $s(t)$ and has a duration δ, then the output $y(t)$ from such a filter in the presence of noise $n(t)$ is given by

$$y(t) = \int_0^{\min\{t,\delta\}} [s(t - x) + n(t - x)]s(\delta - x)dx$$

Previously it was shown that the above integral could be approximated by a summation and the resulting expression could be interpreted in terms of a tapped delay line, weighting networks, and an adding circuit.

The main difficuly which would be encountered in practice in constructing a filter of this type arises from the requirement of a multiple-tapped delay line at the intermediate frequency. The purpose of such a delay line would be to produce a train of equally spaced unit impulses whose amplitudes would be attenuated in accordance with the weighting functions. The envelope of the train of unit impulses would then be the backwards version of the i-f pulse. Under the assumption that the envelope of the i-f pulse is rectangular, it has been found that the multiple-tapped delay line can be replaced by a high-Q tank circuit as is shown in Fig. 3A.

If the unit impulse produced by a current source is applied to the input of the filter of Fig. 3A, the tank circuit will be shocked into oscillation and a damped cosinusoid will be produced at the output. After δ seconds have elapsed the unit impulse will emerge from the delay line and be applied to the tank circuit. The oscillation will be stopped by this second impulse if the resonant frequency of the tank circuit is such that $N + \frac{1}{2}$ (where N is an integer) cycles have been produced in the time δ. If the Q of the tank circuit is sufficiently high the oscillation will be essentially undamped during the time δ and the envelope of the pulse will be rectangular. A Q multiplier[7] can be used in place of the tank circuit if a sufficiently high Q cannot be realized with standard components.

A filter of this type will give a maximum output for i-f pulses which look like the backwards version of its impulse response. However, it can be considered to be the optimum filter for any rectangular i-f pulse with a carrier frequency equal to the resonant frequency of the tank circuit and a pulse width of δ seconds. Any i-f pulse which meets these specifications will coincide with the backwards version of the impulse response over at least N cycles and consequently will produce a maximum output within $\frac{50}{N + 0.5}$ percent of that obtained with a matched pulse. (For example if a pulse width of 0.6 µs and an i-f of 30.8 mc are employed the peak output will be within 2.7 percent of the theoretical maximum.) Design of a filter of this type is in process and construction will probably commence during the next report period.

If similar techniques are used for the synthesis of an optimum filter for video pulses, the multiple-tapped delay line can be replaced by a low-pass filter in a network configuration of the type shown in Fig. 3B. When a unit impulse is applied to the input of the filter an output which has the form of an exponential decay will be obtained. After δ seconds have elapsed a negative impulse will emerge from the delay line and be applied to the input of the low-pass filter. The output will return to zero at this time if the low-pass filter has a time constant which is long in comparison with the delay time δ. Consequently the impulse response of the filter will be a δ-seconds rectangular pulse and the filter will be the optimum one for similar video pulses.

An optimum filter of this type has been constructed for 0.6 µs video pulses and is described under e. Apparatus and Equipment. During this report period it has tested satisfactorily as a correlator for video pulses. During the next report period the operation of the filter in the presence of noise will be evaluated.

Coding Circuitry

It was suggested by AFCRC that work under Item III be begun with emphasis placed on the design, construction, development, and evaluation of a reliable shift register for use in the encoder components of the overall IFF system. The fact that several of these are required, and some are involved in airborne equipment, makes it necessary that weight be reduced to a minimum. Hence, it is desirable to consider the use of transistors instead of vacuum tubes for such devices.

For the purpose of the intended application, the following specifications can be set: The input to the register will consist of 16-digit binary numbers, each pulse having a width of 0.1 to 0.3 µs, and the pulses spaced by 1 µs. The register is to be arranged for either serial or parallel read-in, and either serial or parallel read-out. The loading at present is unspecified; however, it will be necessary as the circuit develops to investigate this aspect since the registers in practice will be connected to such devices as matrix switches.

Figure 4 is a block diagram of such a system arranged for simplicity to accommodate a four-place pulse train. Further details of the basic logic circuits used in the block diagram are given in Fig. 5. The heart of the unit is the storage cell, and work to the present has been concentrated on a circuit following the scheme of Fig. 5A. In this storage cell, the delay is equal to the digit period; hence, the pulse is circulated (or stored) whenever the second input to the "and-gate" is present, and stopped when it is not present. The amplifier presently being employed* is a regenerative one employing a Transistor Products Type 2C transistor, with feedback provided through an inductance in the base circuit. The delay line is a potted, lumped-constant, line having a characteristic impedance of 500 ohms and a delay of 1 μs. The other circuits shown are conventional, and have been fully described in the literature.[8,9,10]

Experimental work to date has been concerned with the construction and test of a single storage cell of the above type. Fifty transistors have been procured and tested, and appear to have characteristics suitable for this application. Auxiliary specialized test equipment is required before cascaded connections of such stages can be investigated, and this equipment is presently in the process of construction. As soon as this stage of the work is completed, it is intended that an eight-stage storage register will be constructed according to the block diagram of Fig. 6. (For convenience, only four stages are shown.)

Initial work on the circuit of Fig. 6 will make use of the basic logic circuits of Fig. 5. After this has been accomplished, studies will be begun to determine the optimum values of circuit constants and ratings, the usable range of transistor characteristics, and other factors essential to high performance reliability. An attempt will be made to meet the conflicting requirements of using a minimum number of components, yet allowing transistor interchangeability.

The timing diagram of Fig. 7 explains the control and operation of the shift register for serial read-in and parallel read-out. Waveform A represents clock pulses spaced by one microsecond, and provides the basic timing for the complete system. The signal assumed is shown in waveform 1, where the signals are the solid pulses. The signal assumed here consists of numbers (or words); namely, 1011 and 1101. The unshaded pulses are the stored pulses which are held in the first register until a new number is inserted. Waveform B is a control waveform, there being a pulse indicating each digit position in the number (regardless of whether it is a zero or a one). This waveform is used as the inhibiting pulse at the inhibitor block (see Fig. 5D), and prevents the circulation of digits in the storage cells during the time of the number. Waveform D is a control signal used to accomplish parallel read-out. The waveforms for serial read-out and parallel read-in could be similarly arrived at.

e. Apparatus and Equipment

Filtering

Optimum filter. An optimum filter for video pulses has been constructed in order to experimentally verify the theory developed. The block diagram of Fig. 3B indicates that the filter should consist of a phase inverter, delay line, adding circuit, and low-pass filter. The actual circuit of the working filter for 0.6-μs pulses is shown in Fig. 8. Tube T_1 serves as phase inverter,

* The circuit is essentially the same as that suggested by AFCRC, and is presently being used there by J. Maimonis.

T_2 is employed to drive the delay line, and T_3 drives the combination adding circuit and low-pass filter.

Since the theory calls for a linear system, and sensitivity to the pulse-repetition frequency is undesirable, the entire circuit is direct coupled. The output of T_2 is balanced at ground potential, and a feed-back loop is included around the T_1 - T_2 combination in order to improve its stability. Tube T_1 produces a gain of about 30 and the closed-loop gain between the input of the optimum filter and the output of T_2 is slightly less than one. The delay element consists of about a foot of Millen 1350-ohm delay cable and is terminated in its characteristic impedance. The output from the delay line and the input to the circuit are applied to the grids of T_3. The signal produced at the junction of the two 5.6-K resistors connected between the cathodes of T_3 would be proportional to the sum of the signals applied to the grids if the output condenser were removed. As it is, the output impedance at this junction is about 3K, and consequently the introduction of the 0.002-μf condenser creates a low-pass filter with a time constant of about 6 μs. This time constant is long enough, compared to the delay, to produce an impulse response that is essentially rectangular.

The optimum filter has been excited by input pulses which varied between 0.1 and 5 μs in duration and its output has been in accordance with correlation theory. During the next report period, the filter will be excited by pulses immersed in noise, and experimental results compared with theoretical calculations.

Some effort has been devoted to the design of an optimum filter for i-f pulses. At the present time little difficulty is expected with the design of the tank circuit (see Fig. 3A) since a Q multiplier can be constructed if the Q of standard components is not sufficiently high. Difficulty has been encountered, however, in the procurement of a suitable delay element for the i-f band. Commercial delay cables are primarily developed for video pulses and consequently have insufficient frequency response. Supersonic delay lines of the fused-quartz variety do not appear to be suitable for delays as short as 0.6 μs because of third-time-around ringing. Lumped-constant delay lines appear to be feasible for the i-f band yet it is not felt that a special design project is warranted at this time. Consequently, unless another solution becomes apparent, the required delay will be obtained with a reel of about 400 ft of RG62/U coaxial cable. After the i-f filter has been constructed, and testing has indicated that it should be included in an IFF system, the design of a lumped-constant delay line can be undertaken.

Pulse-Train Correlator

Correlator construction. In this report period the various component circuits of the pulse-train correlator working model (discussed in detail in the previous report) were constructed in breadboard form and tested individually. The minor modifications that were found necessary are incorporated in the revised schematics of Figs. 9 and 10. The correlator is now in the process of construction as a complete unit.

Pulse-jamming generator. Construction of the final model of the pulse-jamming generator discussed in the two previous reports has been completed. The shape of the output pulse is approximately the same as the shape of the individual output pulses provided by the pulse-train generator also discussed in the two previous reports.

Low-frequency pulse generator. A source of low-frequency pulses for use in the alignment of the pulse-train correlator has been constructed during this report period. The pulse width is of the order of one millisecond, and the pulse repetition frequency is approximately 80 pps. The output amplitude is variable from 0 to 30 volts, and the output impedance is of the order of 300 ohms.

The pulse is generated by an unsymmetrical free-running multivibrator, the output of which is shaped by a cathode-follower clipper. The cathode return of the clipper stage is an attenuator from which the output pulse is obtained.

Coding Circuitry

In order to properly check the operation of the shift register to be constructed, certain pieces of test equipment will be required. Equipments of this nature, that have been worked on to date, are discussed in the following sections.

Clock-pulse generator. A clock-pulse generator essentially the same as one designed by Project Whirlwind at M.I.T. has been constructed, and is ready for operational checking. This generator will provide 0.1-μs pulses, of 0 to 35 volts amplitude, into a 93-ohm load. The frequency is continuously variable from 200 kc to 5 mc.

Signal generator. A signal generator for storage-cell testing has been constructed and is presently being checked. It provides a series of four 0.1-μs pulses spaced at 1-μs intervals, at a repetition rate of 100 cps to 200 kc. Simultaneously, a four-digit word, with the digit places controlled by toggle switches, is generated. The output amplitude of both sets is variable from approximately 0 to 40 volts.

Constant-current source. A constant-current source has been constructed, and its operation checked. The unit consists of two independent supplies built on the same chassis, one supplying positive current, and the other negative current. The supplies have essentially the same component circuits as the Transistor Products Model T61 Transtester. Measured regulation curves are shown in Fig. 12. It is expected that this supply will also be useful in the transistor-testing program.

Transistor Testing

During this report period the organization of the transistor-testing program has been completed, and measurements of the various large and small-signal parameters have been made for a large number of transistors of varying manufacture. Table I of the Appendix gives specific details of the numbers tested.

A Transistor Products Model T61 Transtester has been purchased for the measurement of the usual small-signal parameters; namely, alpha (α) and the standard four-terminal network resistances r_{11}, r_{12}, r_{21}, and r_{22} for the point-contact type, and the corresponding quantities for the junction type[11]. This unit has been used for both the point-contact and junction types of transistors, as indicated in Table I.

The frequency-response characteristics of point-contact transistors are determined by measuring α as a function of frequency, and defining the frequency where alpha is 3 db below its value at 5 kc as the cut-off frequency. Large-signal testing is being used to provide values for rise time, fall time, and hole-storage (or turn-off time). The equipment used in making these tests has been described in the previous report.

A square-wave generator useful for transistor testing and similar applications has been constructed during this report period. The schematic of this device is shown as Fig. 12. It has been designed to provide a constant-amplitude square-wave output, having a frequency of either 500 cps or 100 kc. The rise and fall times are less than 0.05 μs between the 10-percent and 90-percent points, and the peak output amplitude is 15 volts into a load of 200 ohms. A 5-volt synchronizing pulse of either positive or negative polarity is provided.

g. Conclusions and Recommendations

As a result of the work of this report period it is concluded that:

1. If the amplitudes of both signal and noise are of Gaussian distribution, and if the threshold effect is discounted, there is always an increase in the average information when the signal power is divided equally among n channels and the noise power in each channel remains the same.

2. A channel transmitting binary digits has a capacity which depends upon the signal-to-noise ratio and upon the characteristics of the system of detection. Redundancy codes can be devised to permit reliable transmission at a rate approximating the channel capacity, but it appears that rate of transmission should be sacrificed for simplicity of coding in order to avoid very complex equipment problems.

3. The various component circuits of the pulse-train correlator, as modified, operate satisfactorily.

4. The simple circuitry involved in the optimum filter for video pulses demonstrates the practicability of this type of filtering for video pulses.

5. The techniques suggested in this report for constructing an optimum filter for application in the i-f section of a pulse receiver appear to be practical.

6. The present transistor-testing program is providing sufficient useful information regarding transistor parameters and performance to allow competent circuit design and classification of transistors according to their frequency response, small-signal alpha, etc.

7. The pulse-jamming generator produces pulses of approximately the same shape as that of the individual output pulses of the pulse-train generator, and as a result should be effective as a jamming device for testing the system under study.

8. The fixed-frequency square-wave generator is a useful piece of test equipment for specific applications, and thus will serve to free similar commercial equipment for general laboratory use.

9. The operation of the constant-current source appears satisfactory for transistor applications.

10. The signal generator for storage-cell testing will adequately fulfill its purpose when it has been completely checked out.

11. The clock-pulse generator for storage-cell testing will be satisfactory for both its intended usage and as a general laboratory item.

As an alternative to the general system covered by this and previous reports, it is recommended that consideration be given to a system which employs random noise as a challenge. The random noise would be processed by a linear or non-linear network in the transpondor, whose parameters constitute the code of the sortie period.

h. Future Work

In view of the work of this and previous report periods, and the above conclusions and recommendations, it is intended that future work include:

1. Studies directed toward the determination of the optimum signal for IFF purposes. Consideration will be given specifically to the applicability of noise-like waveforms to this problem.

2. The continuation of various studies of a general nature that have already been begun. These include (a) the study of contemporary jamming and countermeasures techniques, (b) the study of ways by which correlation and filtering methods can be applied to IFF systems to improve system reliability, and (c) the study of the response of video detectors to pulses in the presence of noise.

3. Further general study of redundancy coding, with special emphasis placed on the consideration of the probability distribution of the envelope of noise and signal combined. Practical consideration will be given to determining the feasibility of employing redundancy-coding techniques as means for improving the reliability of IFF systems.

4. The completion of the pulse-train correlator and the testing of this unit to determine (a) the optimum values of the design parameters for various conditions of noise and pulse jamming, and (b) the amount of jam rejection possible with this device.

5. The testing of the optimum filter for video pulses to determine its operation in the presence of noise. Experimental results will be compared with its calculated performance.

6. The construction and testing of an optimum filter for application in the i-f section of a pulse receiver.

7. The continuation of the study and design of a storage cell suitable for use as the memory element in a shift register. All immediate work under Item III will be directed toward the development of a reliable transistorised shift register.

8. The continuation of the transistor-testing program in its present form to provide design data upon which to base the work on transistor circuitry carried on at Northeastern and AFCRC.

APPENDIX

a. Curves and Drawings

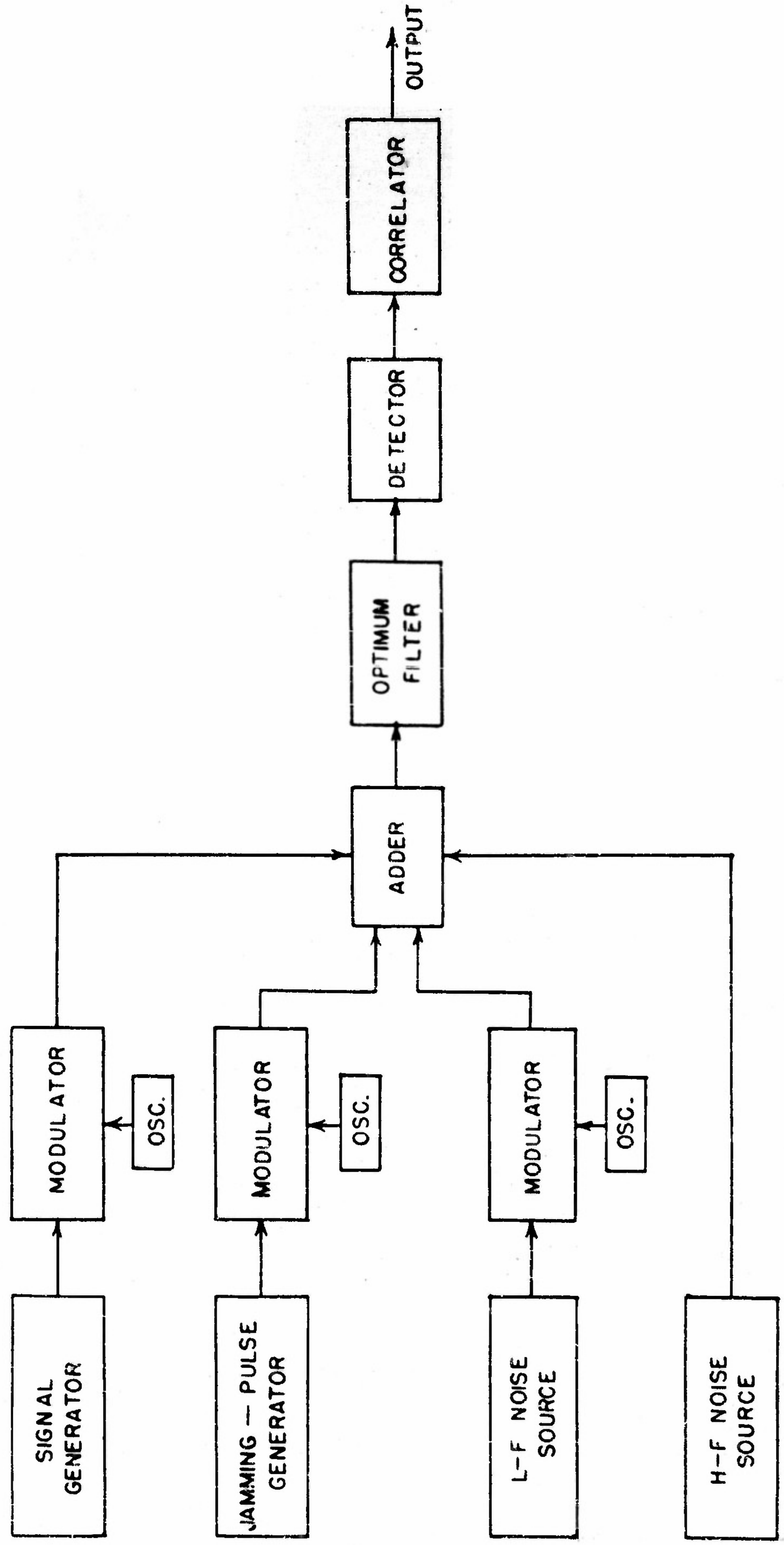


FIG. I. BLOCK DIAGRAM OF PROPOSED TEST SET-UP.

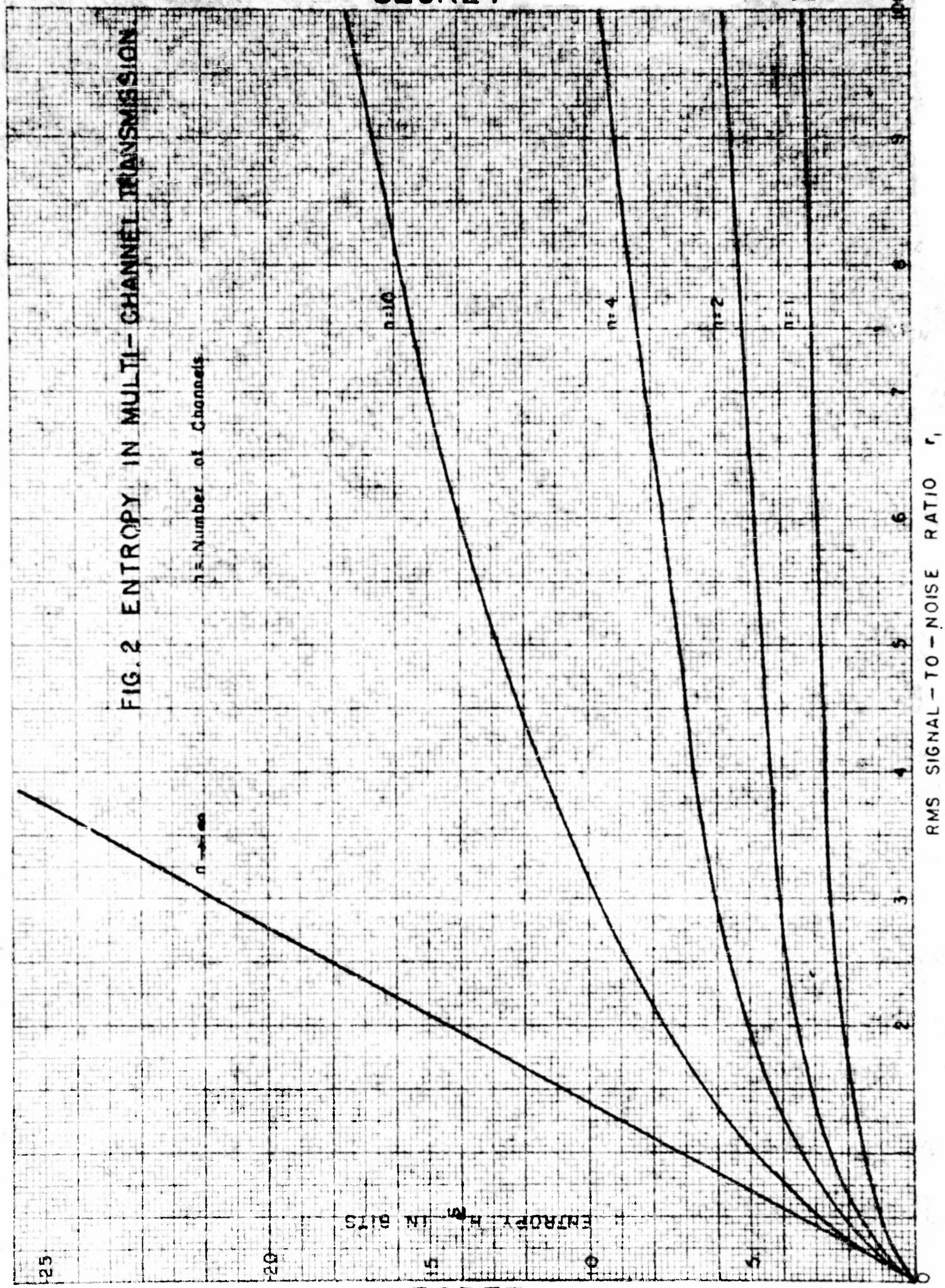
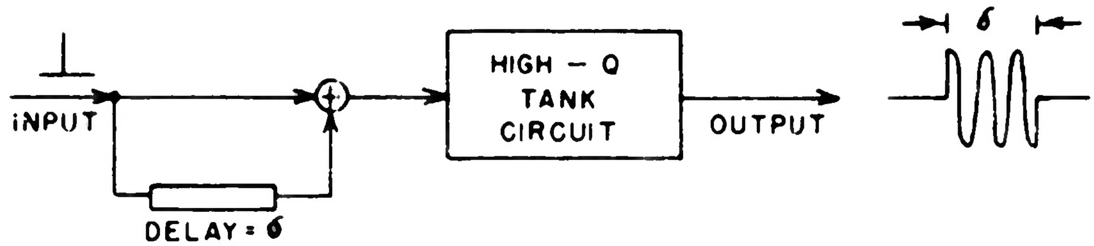
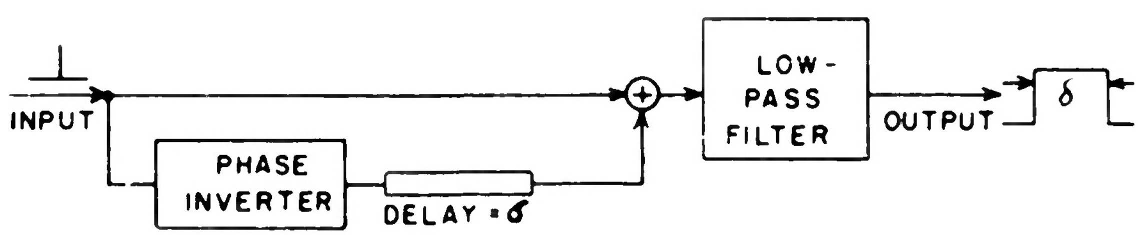


FIG. 2 ENTROPY IN MULTI-CHANNEL TRANSMISSION



A. OPTIMUM FILTER FOR I-F SECTION.



B. OPTIMUM FILTER FOR VIDEO PULSES.

FIG. 3. OPTIMUM FILTERS.

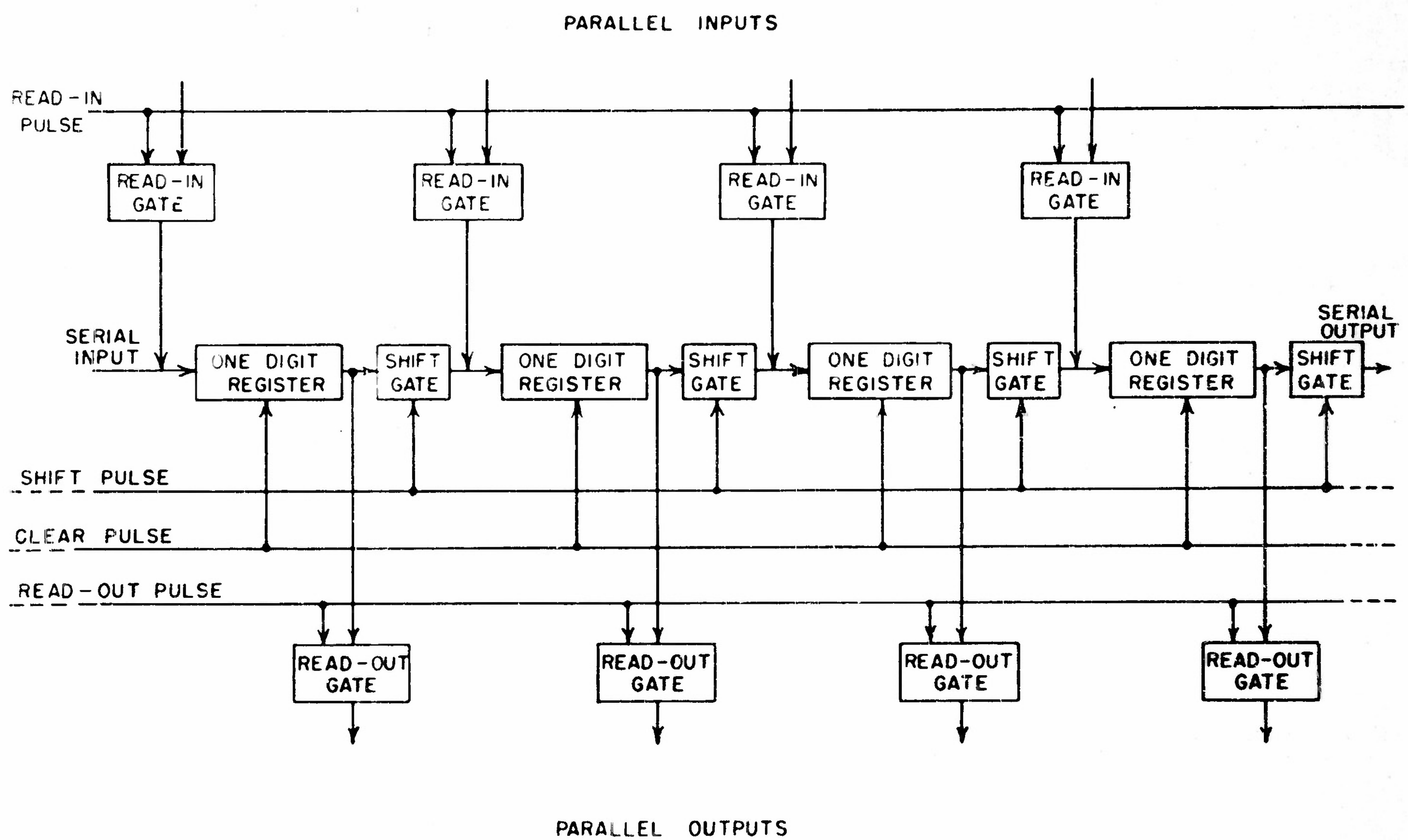


FIG. 4. SHIFT REGISTER FOR SERIAL AND PARALLEL READ-IN AND READ-OUT.

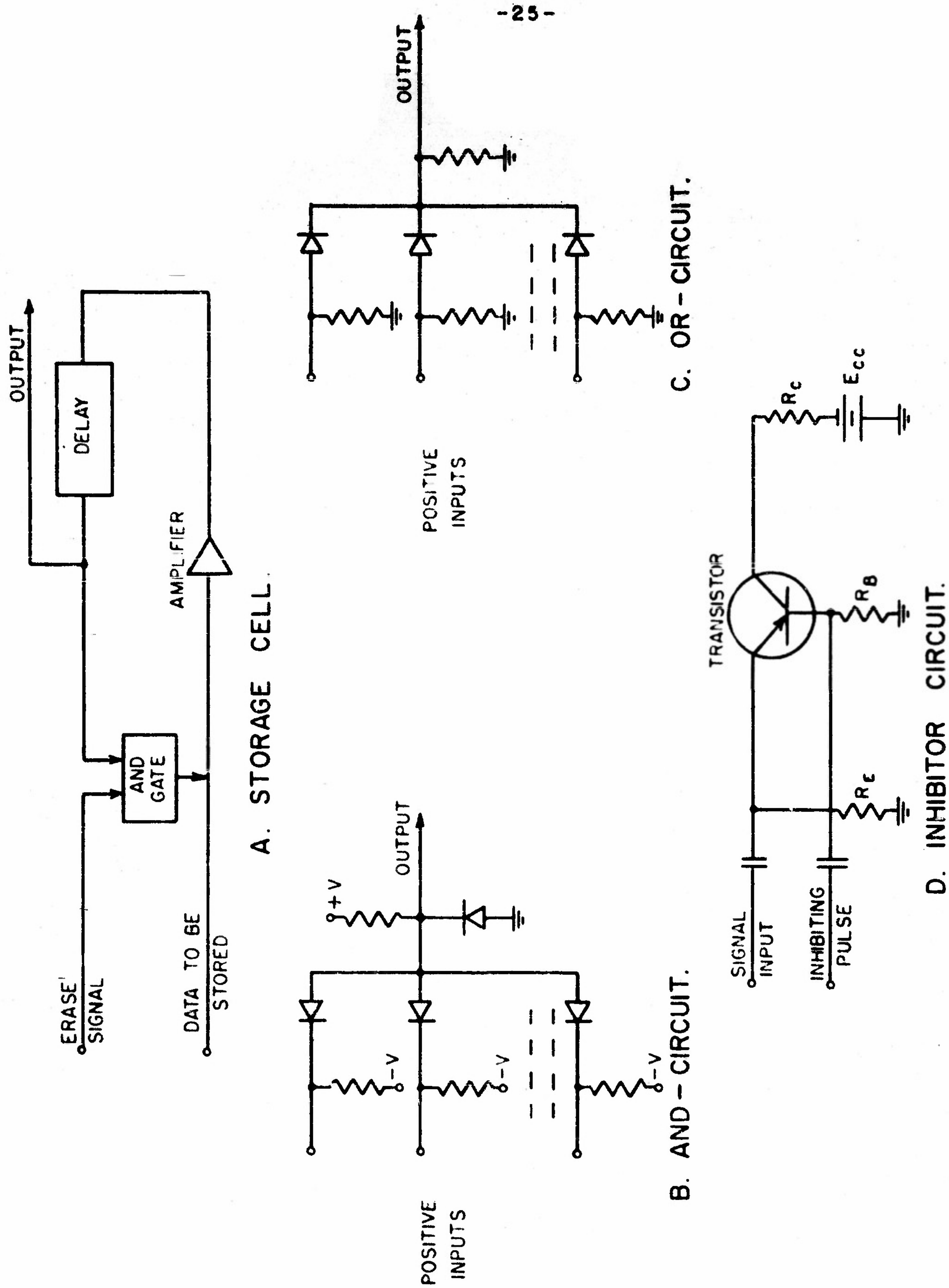


FIG. 5. BASIC LOGIC CIRCUITS.

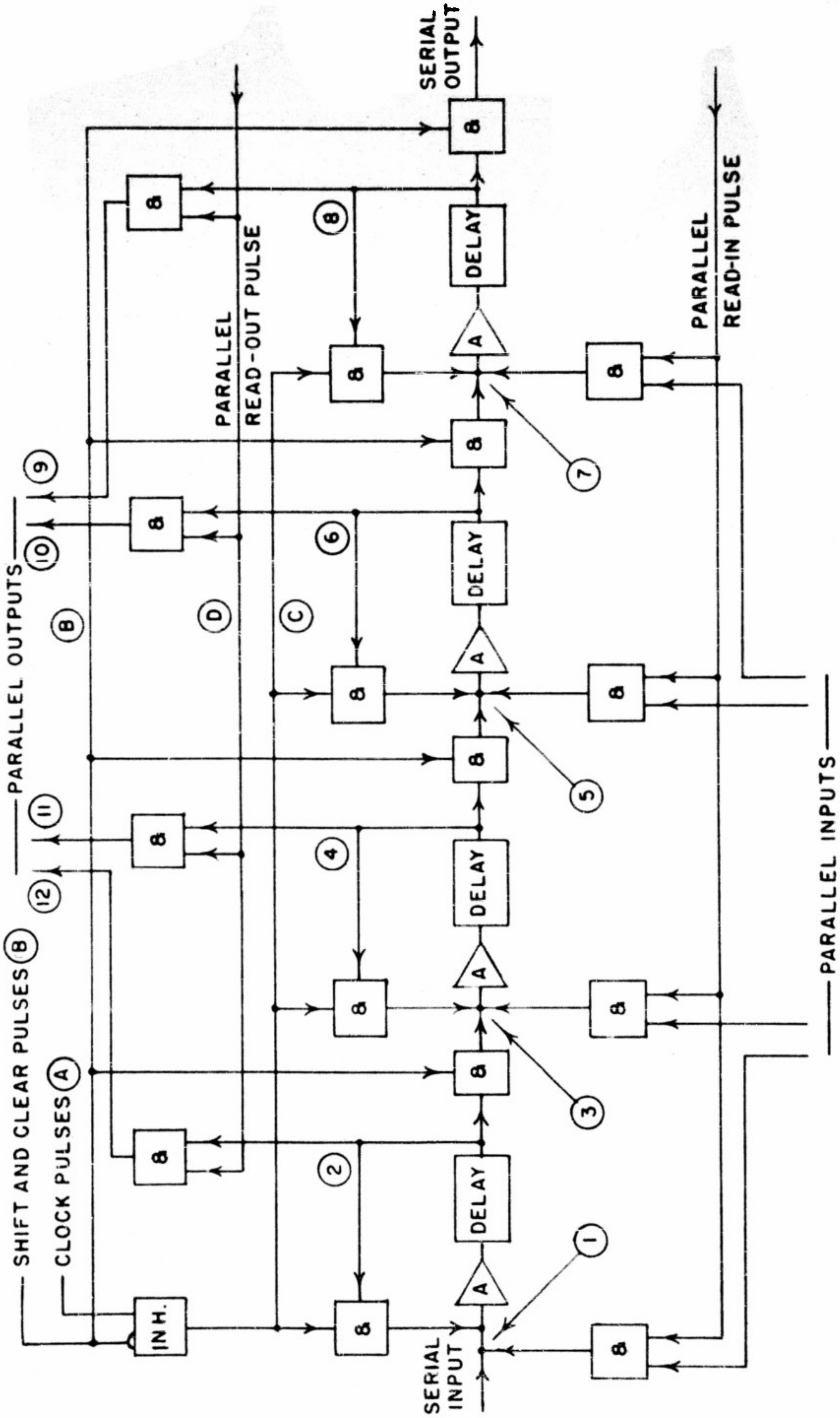


FIG. 6. SHIFT REGISTER USING ACTIVE DELAY-LINE STORAGE CELL.

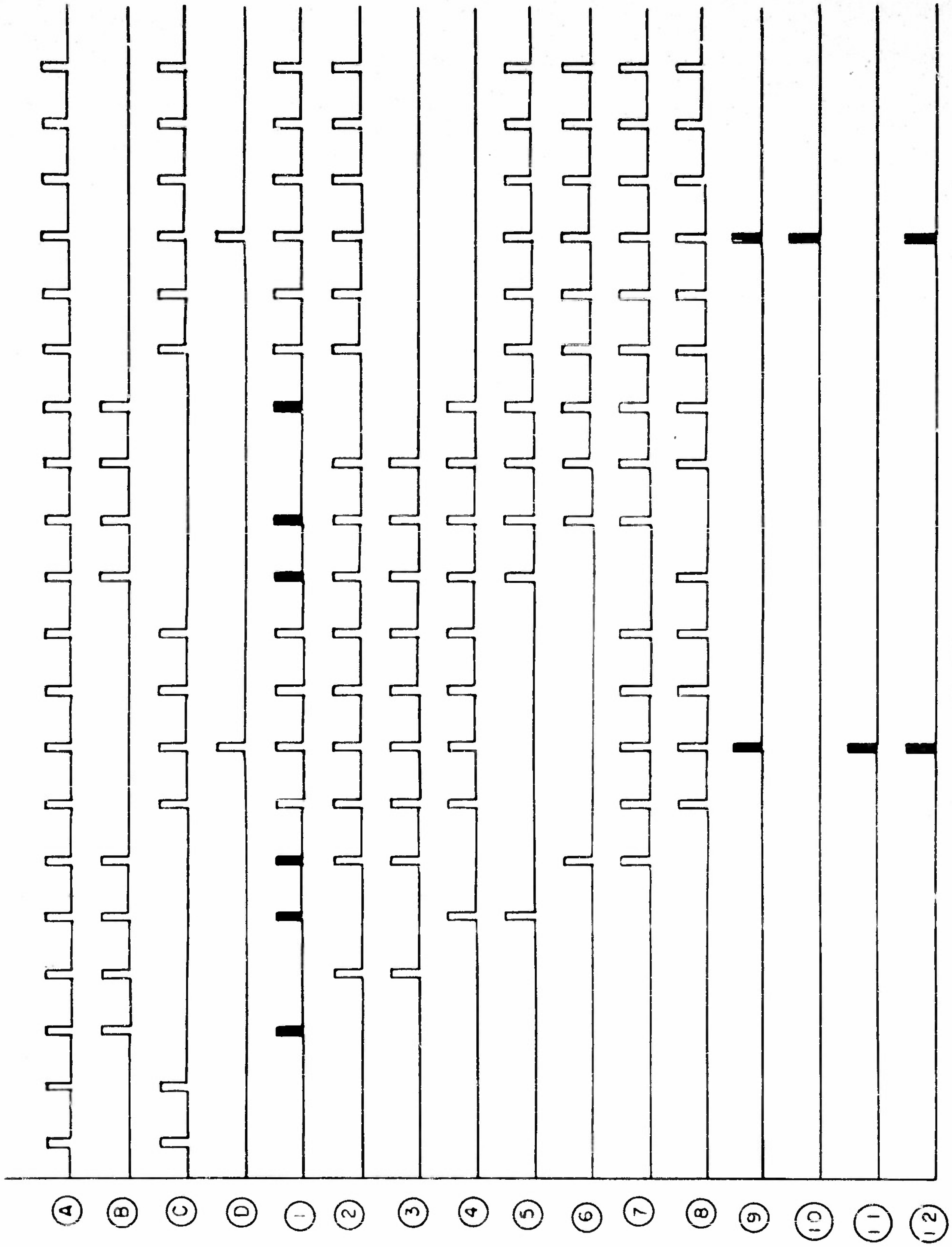
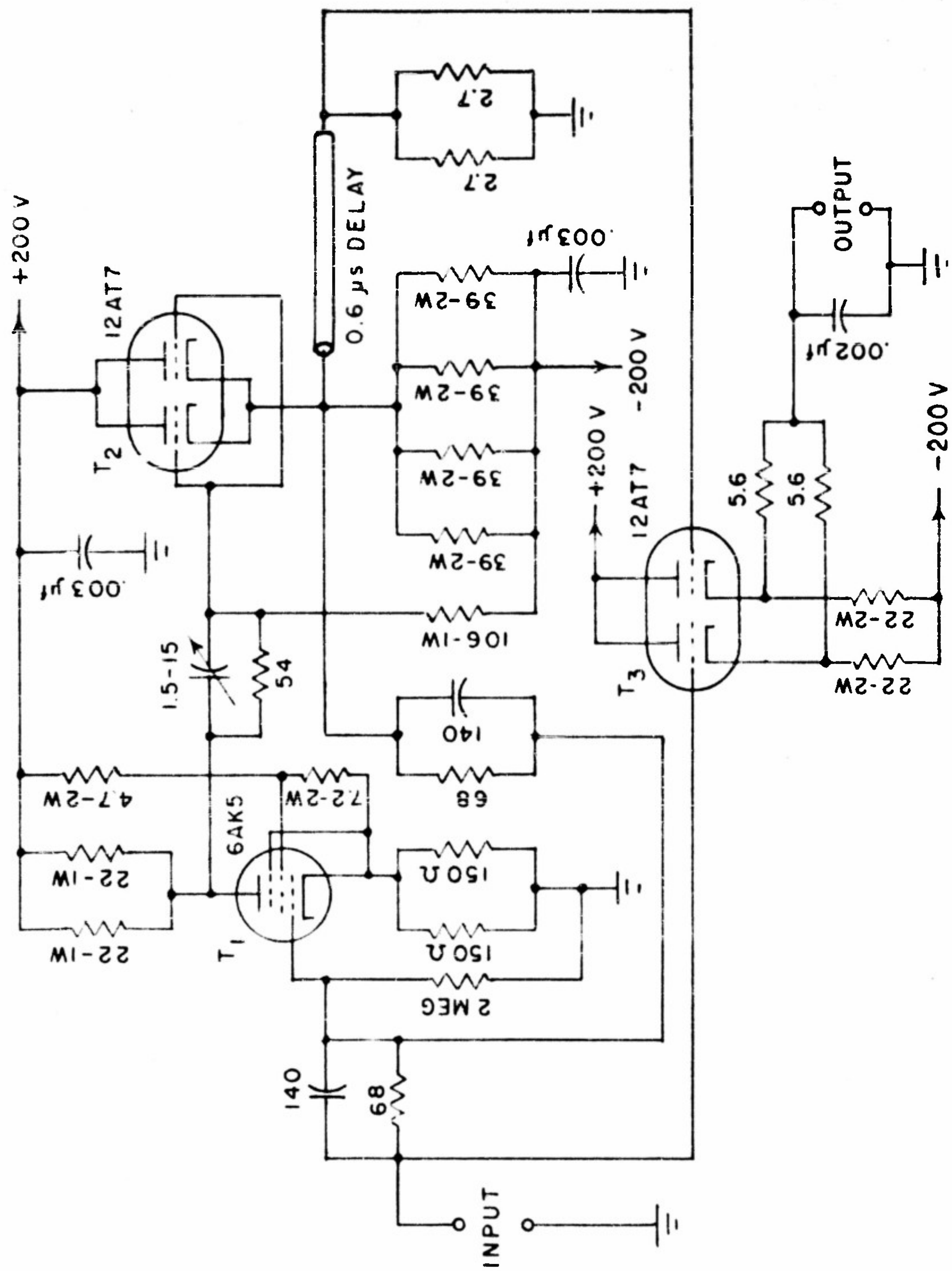
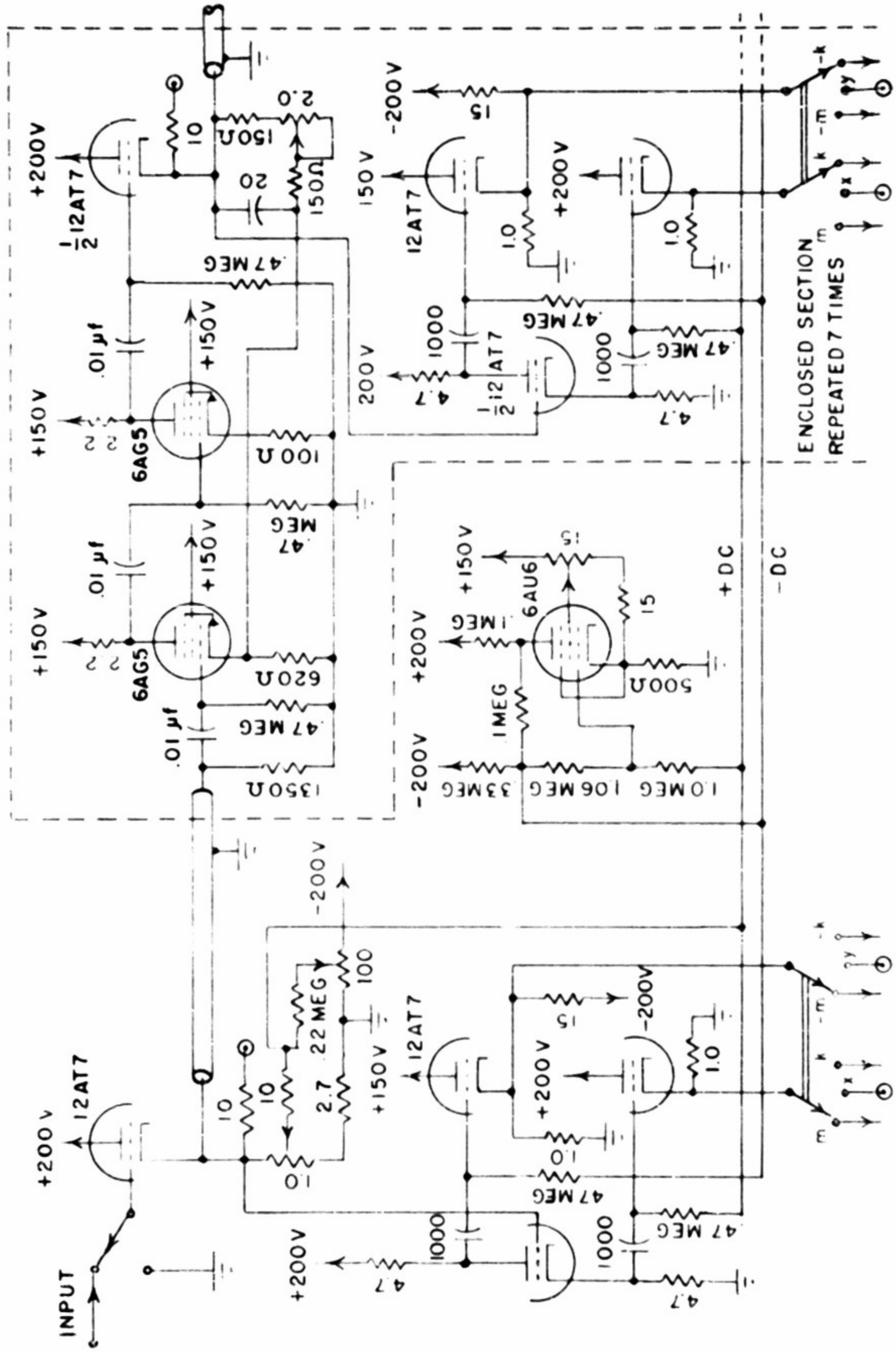


FIG. 7. TIMING DIAGRAM FOR SERIAL READ-IN AND PARALLEL READ-OUT OF SHIFT REGISTER.



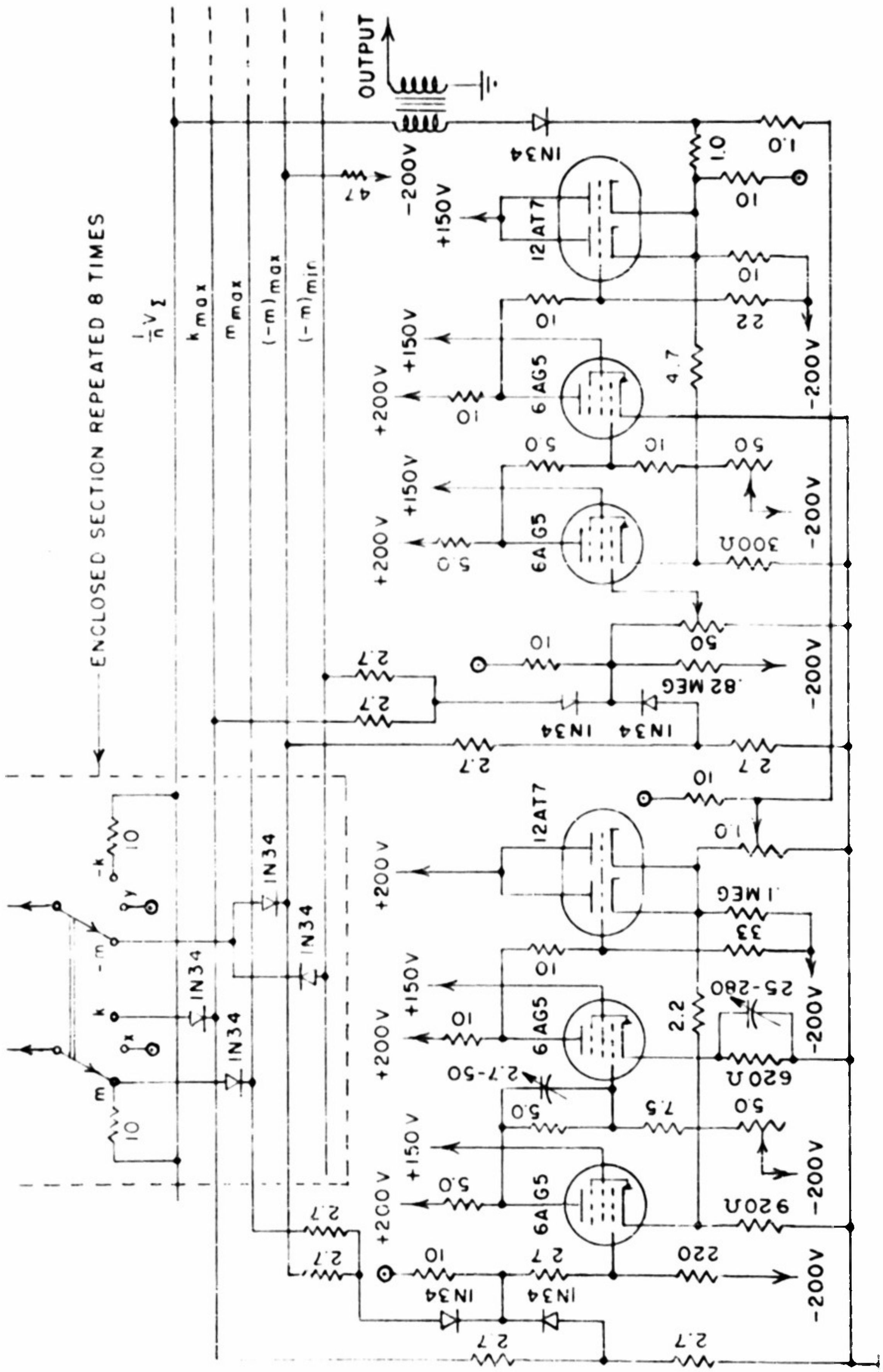
NOTE: ALL RESISTORS ARE 1/2 WATT UNLESS OTHERWISE SPECIFIED.
ALL RESISTANCE VALUES IN KΩ AND ALL CAPACITANCE VALUES IN μμf UNLESS OTHERWISE SPECIFIED.

FIG. 8. OPTIMUM FILTER FOR 0.6μs VIDEO PULSES.



NOTE: ALL RESISTANCE VALUES IN KΩ AND ALL CAPACITANCE VALUES IN μμf UNLESS OTHERWISE SPECIFIED.

FIG. 9 MODIFIED SCHEMATIC OF PULSE-TRAIN CORRELATOR (FIRST HALF).



NOTE: ALL RESISTANCE VALUES IN KΩ AND ALL CAPACITANCE VALUES IN $\mu\mu f$ UNLESS OTHERWISE SPECIFIED.

FIG. 10. MODIFIED SCHEMATIC OF PULSE-TRAIN CORRELATOR (SECOND HALF).

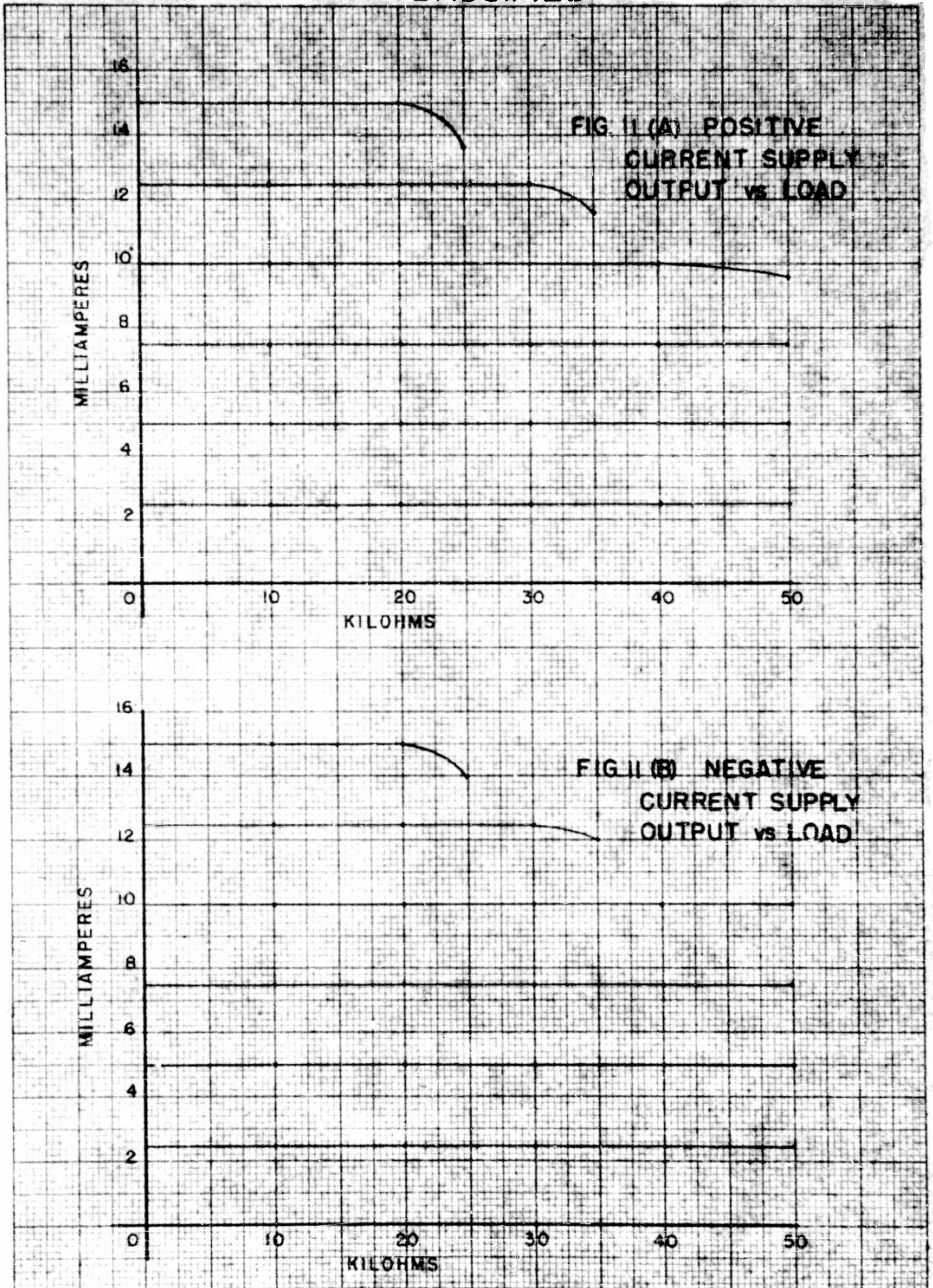
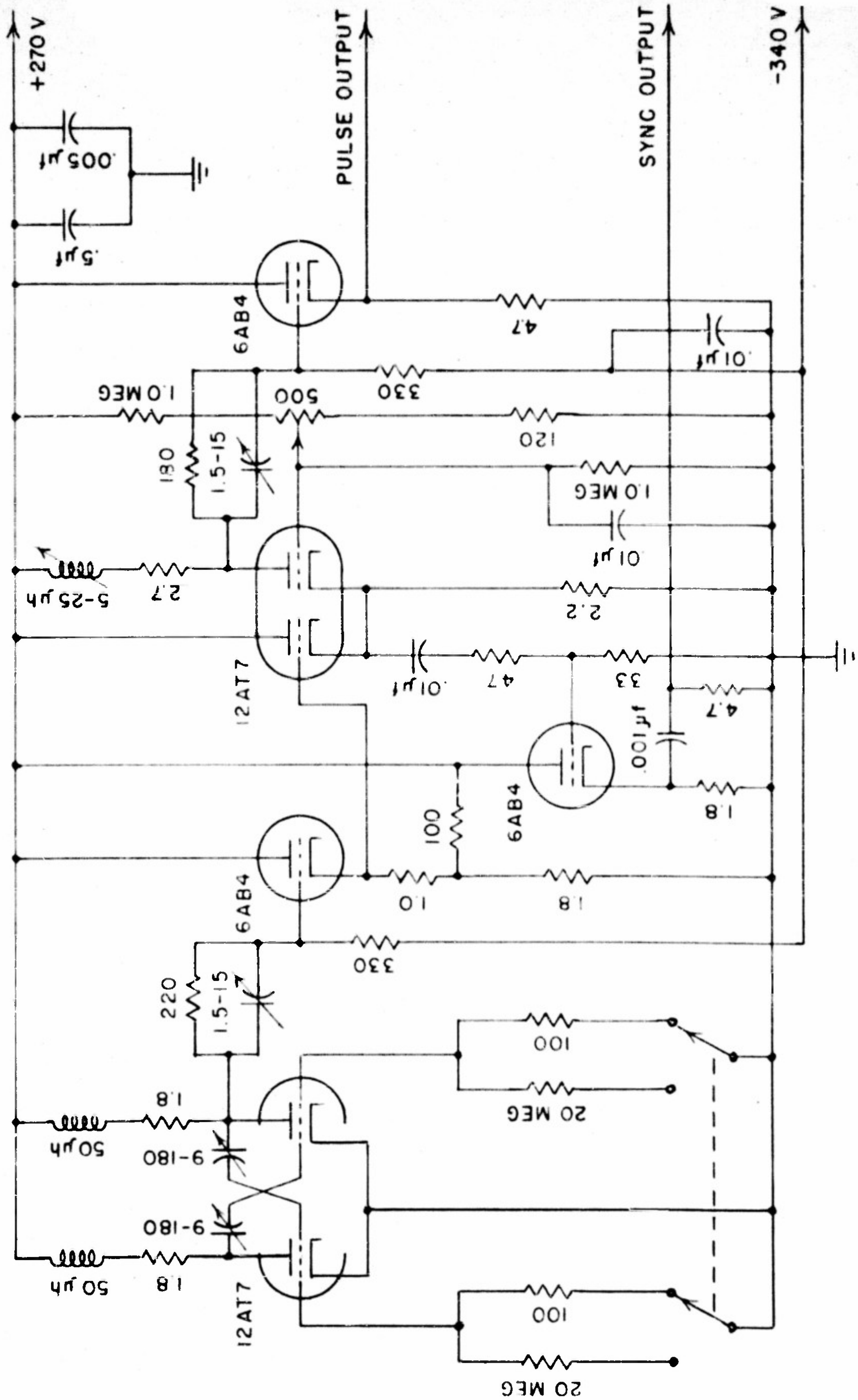


FIG. 11. REGULATED CURRENT SUPPLY CHARACTERISTICS



NOTE: ALL RESISTANCE VALUES IN KΩ AND ALL CAPACITANCE VALUES IN μμf UNLESS OTHERWISE SPECIFIED.

FIG. 12. FIXED-FREQUENCY SQUARE-WAVE GENERATOR.

TABLE I

Point-Contact Transistors

Manufacturer and type	No. tested	r_{11} ohms	r_{12} ohms	r_{21} kilohms	r_{22} kilohms	α	Cut-off freq,mc	Rise time,μs	Fall time,μs	Hole storage time,μs
Western Electric Type 1698	186	140-710	30-360	4-200	5-100	1-3.2	.07-4.4	.096-2.54	.127-2.92	1.02-5.26
Western Electric Type 1768	279	160-390	35-155	15-60	6-17	1-4.4	.21-1.84	.13-1.52	.26-1.94	1.5-11.2
RCA Type TA165	18	155-470	45-190	8-99	16-46	1.6-3.25	1.3-5.4	.03-.38	.03-.38	0.13-1.02
Transistor Products Type 2A	6	220-440	60-250	6-115	15-40	1.9-3.0	0.3-2.1	.38-1.15	.64-1.65	.83-6.62
Transistor Products Type 2C	50	190-1400	80-830	19-148	6-38	1.9-4.1	.92-5.0	.063-.508	.040-.555	
Transistor Products Type 2D	5	160-410	60-330	39-90	14-36	2.3-3.1	1.7-3.0	.125-.320	.125-.320	
Transistor Products Type X10	57	120-4.2K	40-350	17-79	7-37	1.6-4.2	1.1-5.7	.03-.44	.03-.70	
Raytheon Type CK716	41					1.0-2.25	.058-5.5	.04-1.5	0.13-1.91	.06-4.06

Junction Transistors

Manufacturer and type	No. tested	r_e ohms	r_g ohms	r_c megohms	r_m megohms	α
B.T.L. Type M1752	6	14.6-36.9	208-600	.83-10.5	.81-21.8	.961-.979
Raytheon Type CK721 CK722	6	15.8-27.5	92-745	.8-1.49	.7-1.03	.870-.976
Germanium Products Type 2517	8	21.1-42.44	10-345	.23-4.76	.192-4.30	.835-.995

UNCLASSIFIED

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